

DETERMINING THE OPTIMAL PERFORMANCE BASED STANDARDS HEAVY VEHICLE DESIGN

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The Performance Based Standards (PBS) approach for heavy vehicles is currently being evaluated in South Africa (SA). This study evaluated the potential improvements in productivity and vehicle safety that would be achieved if a heavy vehicle is designed according to the PBS approach. Approximate models to estimate Static Rollover Threshold (SRT), Low-Speed Swept Path (LSSP) and Rearward Amplification (RA) were implemented in an optimisation routine which automated the design process for 4 vehicle configurations with payload densities from 50 kg/m^3 to 800 kg/m^3 . The procedure used a new regression model to estimate RA for a broad range of vehicle configurations. The design routine was run using both PBS constraints and those of the current SA legislation to allow direct comparison. The results indicate that heavy vehicles designed according to a PBS approach are safer than vehicles designed according to the current SA legislation. PBS vehicles only achieve higher productivity when transporting payload densities greater than 400 kg/m^3 .

Keywords: South African heavy vehicle legislation, PBS, vehicle safety, payloads, vehicle dynamics simulation, design automation, Smart Truck.

1. Introduction

The Performance Based Standards (PBS) approach to heavy vehicle legislation provides a framework to allow vehicles that exceed current legal prescriptive mass and dimension limits access to the road network, under condition that the proposed vehicle's safety is demonstrated either through physical testing or simulations. Such a PBS approach is currently being evaluated in South Africa for its potential to improve productivity, and road safety and reduce wear on infrastructure.

This evaluation process currently involves demonstration projects of heavy vehicles designed using the PBS legislation used in Australia. Operators may apply for permission from the relevant South African PBS Abnormal Load Permit Office(s) and the Smart Truck Review Panel to operate a demonstration vehicle or fleet of vehicles. The vehicle design must adhere to the Australian PBS rules and the vehicle or fleet is carefully monitored to confirm its improved productivity and safety performance compared with the baseline vehicles (Nordengen *et al.*, 2008). This process has been successful in demonstrating the benefits of PBS for a small number of cases and in a few industries. Although interest is growing in this initiative and new PBS vehicle designs are being developed, the process is expensive and can take more than 2 years (CSIR, 2012). A major portion of this time is spent in design phase iterations as the designs are proposed by the operator and manufacturers and then evaluated using complex computer simulations by a separate expert. The time and cost associated with this process is a major barrier to entry.

In this study, an automated design routine is proposed to quickly evaluate various vehicle configuration options for a given payload density to establish whether a PBS design has the potential to offer a solution with improved productivity or safety (or both) without costly detailed design upfront.

This design routine was used to evaluate the potential improvements in productivity and vehicle safety that could be achieved using the PBS framework over current South African vehicle legislation. The results of this study will aid the South African road authorities in evaluating the potential benefits of introducing PBS legislation.

2. Methodology to Develop an Automated Design Routine

As noted by Fancher and Winkler (2007) PBS measures could be considered during the design development if they are incorporated in the design process through the use of simple models that can be evaluated at low computational cost. A South African PBS vehicle (or Smart Truck) must conform to the following safety performance measures defined by the Australian National Transport Commission (2008): Yaw Damping Coefficient (YDC), Static Rollover Threshold (SRT), Rearward Amplification (RA), High-Speed Transient Offtracking (HSTO), Tracking Ability on a Straight Path (TASP), Low-Speed Swept Path (LSSP), Frontal Swing (FS), Difference of Maxima (DoM), Maximum of Difference (MoD), Tail Swing (TS), Steer-Tyre Friction Demand (STFD), Startability, and Gradeability.

While the above measures are necessary and sufficient for a full PBS assessment in SA, only the following measures were incorporated into the automated design routine: Static Rollover Threshold (SRT), Rearward Amplification (RA), Low-Speed Swept Path (LSSP), Frontal Swing, Tail Swing, Startability, and Gradeability.

The reduced set of performance measures allowed the design routine to run quickly enough to be automated using optimisation. The intention is that once the design routine has given a near-optimal solution, a detailed PBS assessment, including the full set of performance measures, could be undertaken to fine-tune the design to ensure the vehicle is fully PBS compliant.

The Australian PBS guidelines contain requirements that are specific to the road class to which the vehicle is permitted access; requirements are more lenient for the higher road levels (National Transport Commission, 2007):

- Level 1 (L1) – General Access
- Level 2 (L2) – Significant Freight Routes
- Level 3 (L3) – Major Freight Routes (generally the lowest level met by road trains)
- Level 4 (L4) – Remote Areas

The PBS limits for Level 2 access were selected for this study as it would be the most applicable for the major highway transit routes in South Africa.

2.1 Estimates of PBS Performance

Static Rollover Threshold (SRT)

The SRT was predicted using the method developed by Elischer and Prem (1998):

$$SRT = \frac{T}{2HF} \quad (2)$$

- Where:
- T = track width [m]
 - H = height of centre of gravity for the vehicle (tare and payload) [m]
 - F = $1 + \frac{W_P(H_P - H_E)}{H(W_E + W_P)}$

- Where:
- W_P = payload mass [kg]
 - W_E = empty vehicle mass [kg]
 - H_P = height of centre of gravity of payload [m]
 - H_E = height of centre of gravity of empty vehicle [m]

Low-Speed Swept Path (LSSP)

The LSSP was predicted using the formula proposed by Prem *et al.* (2002) which uses a third order polynomial in terms of the WHI formula equivalent wheelbase, WB_{eq} (1970). The model predicts the LSSP for the Australian PBS turn configuration (90° turn with 11.25 m radius¹) with $r^2 = 0.99$. The prediction of the total road usage includes the equivalent wheelbase of the hauling unit. The equivalent wheelbase is given by:

$$LSSP = \beta_0 + \beta_1 WB_{eq} + \beta_2 WB_{eq}^2 + \beta_3 WB_{eq}^3 \quad (4)$$

¹ The current PBS performance measure for LSSP specifies that the outer surface of the outer steer tyre must remain within a radius of 12.5 m during the turn (National Transport Commission, November 2008). This difference in the definitions generally has only a minor impact on the simulated results for the configurations considered in this study.

Where: $\beta_{0,1,2,3}$ = 1681.5, 197.49, 30.965 and -0.59412 [-]
 WB_{eq} = WHI formula equivalent wheelbase given by:

$$WB_{eq} = \sqrt{\sum WB_i^2 - \sum OS_i^2} \quad (3)$$

Where: WB_i = wheelbase of vehicle unit i [m]
 OS_i = hitch point offsets (fifth wheel and pin type) [m]

Note that the front overhang was included in the wheelbase of the prime mover for the calibration model proposed by Prem *et al.* (2002).

Rearward Amplification (RA)

Existing models to predict RA use regression models for a single vehicle configuration and so cannot be applied to vehicle configurations other than those used to calibrate the model (UMTRI, 1993 and Mueller *et al.*, 1999). A new regression model was therefore proposed to estimate RA for any combination of tractor, rigid truck, semi-trailer, pig/tag trailer, B-type trailer and A-type dollies. The RA was estimated by calibrating a regression model to the results from a parametric study conducted by Prem *et al.* (2002) that covered a range of vehicles representative of the Australian heavy vehicle fleet.

The new RA regression model assumes that the prime mover amplifies the input of the steering signal and that each trailing unit further amplifies this signal by a factor that may be described by linear relationships in terms of the same variables considered in the Australian parametric study (Prem *et al.*, 2002) as shown in equation (4).

$$K_i = \beta_0 + \beta_1 M_i + \beta_2 WB_i + \beta_3 OS_i + \beta_4 H_i \quad (4)$$

Where: M_i = sprung mass of vehicle unit i [kg]
 WB_i = wheelbase of vehicle unit i [mm]
 OS_i = hitch point offset for trailing unit (fifth wheel and pin type) [mm]
 H_i = centre of gravity (CoG) of sprung mass of vehicle unit i [mm]
 $\beta_{0,1,2,3,4}$ = regression coefficients given in Table 1

Note that OS is negative if the hitch point is aft of the centre of the rear axle group of the towing unit.

The total amplification of the lateral acceleration input at the steer axle at vehicle unit n within the combination is then given by the product:

$$RA_i = \prod_{i=1}^n K_i \quad (5)$$

The values of the amplification factors were not directly available from the data set so the model parameters were calibrated using the evolutionary algorithm in the Microsoft Excel 2010 solver (Nenov and Fylstra, 2003). The resulting model predicts the data set of RA of the final unit in the vehicle combination for 95 data points covering 9 vehicle configurations from the parametric study (Prem *et al.*, 2002) with an adjusted $r^2 = 0.990^2$. The model fit is shown in Figure 1.

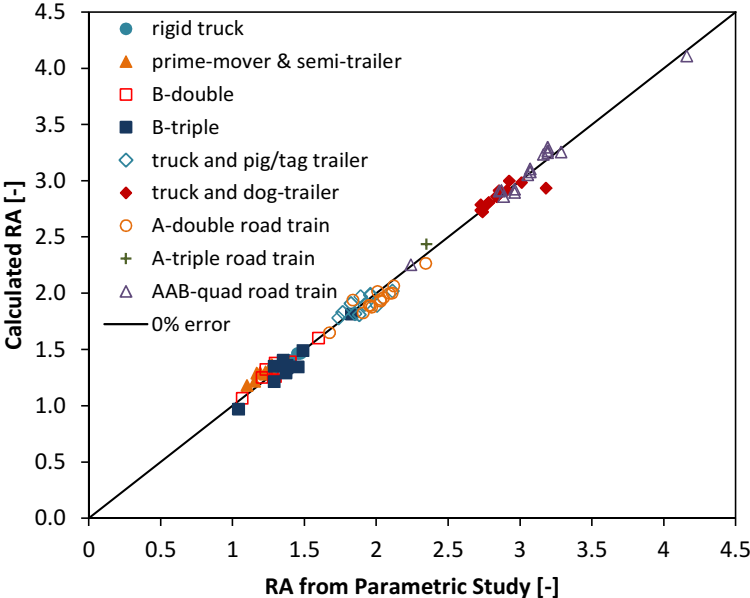


Figure 1 – Comparison of Regression Model for RA to Parametric Data

Equation (5) may be applied using the coefficients in Table 1 to predict the RA for any combination of the base units. The sprung mass coefficient (β_1) can be ignored as its contribution is negligible.

Table 1 – RA Regression Model Coefficients

	Units	Rigid Truck	Tractor	Semi-trailer	B-trailer	A-Dolly
Intercept (β_0)	-	1.450	1.450	1.405	1.305	1.263
Sprung mass (β_1)	kg^{-1}	-1.957E-6	-1.957E-6	-	1.477E-10	7.756E-6
Wheelbase (β_2)	m^{-1}	-0.07345	-0.07345	-0.04974	-0.06788	-0.03410
Hitch point offset (β_3)	m^{-1}	-0.2379	0.2686	-0.09354	2.662E-6	5.535E-7
Sprung mass CoG (β_4)	m^{-1}	0.1676	0.1676	2.464E-3	0.1183	2.409E-3*

* using CoG of towed unit

The definition of the RA measure combines the lateral acceleration of each unit in the rearmost roll coupled unit at each time instant during the manoeuvre into a single resultant lateral acceleration using a weighted average of the lateral accelerations of each unit within the roll-coupled set. The peak of this effective lateral acceleration is used to calculate the RA

² Estimates of input variables not listed in the report were made based on the wheelbase lengths and vehicle configurations.

for the full vehicle combination in accordance with the new definition used by the Australian National Transport Commission (2008). The same formula was applied with the new model to the per-unit RA calculated using equation (5) to give an estimated RA for the rearmost coupled unit, RA_{rcu} . The generalised form for N vehicle units in a roll-coupled unit is given by:

$$RA_{rcu} = \frac{\sum_{i=1}^N RA_i M_i H_i}{\sum_{i=1}^N M_i H_i} \quad (6)$$

Where: RA_i = RA of vehicle unit i estimated using regression model [-]

M_i = sprung mass of vehicle unit i [kg]

H_i = centre of gravity of sprung mass of vehicle unit i [mm]

It is important to note that this approach, which uses the estimated peak lateral for each unit, is expected to overestimate that calculated from a detailed simulation done at each instant during the manoeuvre since the response of each unit is usually out of phase with units ahead of it. This is demonstrated in Figure 2 which compares the estimated RA_{rcu} to the results from detailed simulations performed with the multi-body vehicle dynamics software package TruckSim 8.01 using generic suspension and tyre parameters as described in Prem *et al.* (2001) (the combinations were selected for their high RA). This approach is considered suitable for the purposes of this study since the results are conservative and therefore do not increase bias towards PBS vehicle designs over those configured to meet the prescriptive South African legislation.

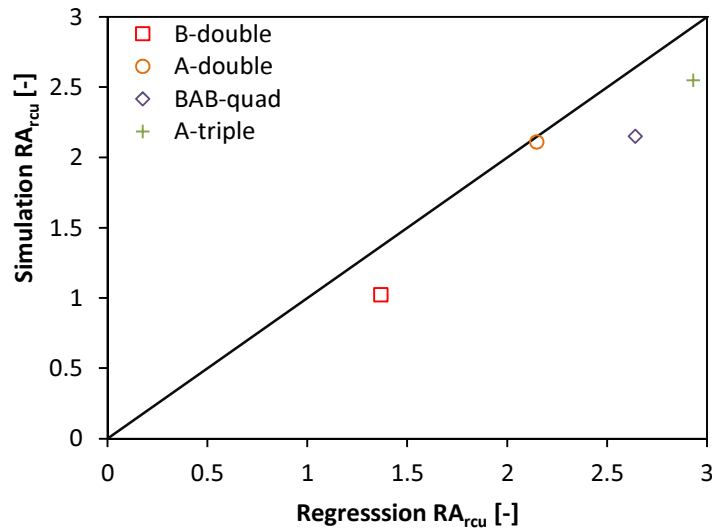


Figure 2 - Comparison of Simulation RA_{rcu} to Regression Model Estimates

Frontal Swing (FS) and Tail Swing (TS)

The PBS analysis of the Australian heavy vehicle fleet (Prem *et al.*, 2002) was used to establish conservative limits for vehicle unit front and rear overhang to limit the vehicle's FS and TS to acceptable limits for PBS vehicle allowed access to L2 routes. These limits were set to 1.6 m and 3.9 m for front and rear overhang respectively.

Startability and Gradeability

A maximum vehicle gross mass of 85 000 kg was selected to ensure the vehicle designs would meet the requirements for Startability and Gradeability. The individual mass limits for these standards are shown in Table 2.

Table 2 – Conservative Mass Limits for L2 PBS Vehicle

Startability	105 000 kg
Gradeability - Maintain Motion	85 000 kg
Gradeability - Maintain Speed	100 000 kg
Minimum	85 000 kg

A further constraint was set to ensure that the axle load carried by the drive axle unit provides sufficient traction so that the vehicle meets both the Startability and Gradeability L2 grade limits of 12% and 15% respectively (assuming that a drive train with sufficient power is selected). A coefficient of friction of 0.8 was used as specified in the PBS requirements (National Transport Commission, Nov 2008).

Overall Vehicle Length, Axle Load and Bridge Loading Constraints

Level 2 limits overall vehicle length to less than 30 m to ensure safe overtaking times (National Transport Commission, 2008).

PBS vehicles must adhere to the South African restrictions on axle loads as prescribed in Government Gazette No 20963, Part 1 (Department of Transport, 2000) are summarised in Table 3.

Table 3 – South African Axle Mass Load Limits

Configuration	Limit [kg]	Regulation
2 wheel, 1 axle, steerable	7 700	240 (b)
4 wheel, 1 axle	9 000	240 (c)
8 wheel, 2 axle	18 000	240 (e)
12 wheel, 3 axle	24 000	240 (g)

In addition the South African bridge formula was applied as per Equation (1). The formula limits the concentration of axle loading in the longitudinal direction to prevent bridge overloading³ (Department of Transport, 2000).

$$P = 2100L + 18000 \quad (1)$$

Where: L = distance between the centres of extreme axles of any two axle groups [m]

P = maximum combined mass on all the axles within the distance L [kg]

³ Recent Smart Trucks projects in South Africa have been permitted to use an alternative abnormal bridge load formula that allows greater longitudinal axle load concentration.

2.2 Design Routine Implementation

The optimisation routine adjusted the following parameters:

- vehicle configuration e.g. rigid truck, B-double etc.;
- wheelbases of all applicable vehicle units;
- number of axles per axle group;
- payload height, length and location; and
- hitch offset

The following vehicle configurations were considered (See Figure 3): truck and pig/tag trailer, truck and dog trailer, B-double and A-double.


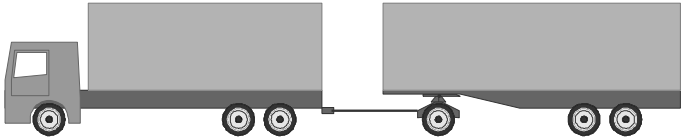
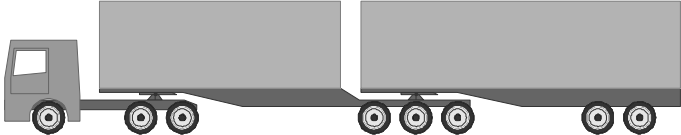
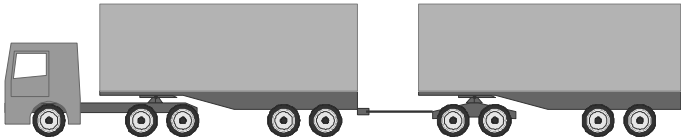
<u>Configuration</u>	<u>Description</u>	<u>Short Code</u>
	Truck and pig/tag trailer	TP
	Truck and dog trailer	TDS
	B-double	TBS
	A-double	TSDS

Figure 3 – Vehicle Configurations

The vehicle payloads were modelled as a box with uniform density and the maximum acceptable width of 2.6 m under the South African legislation (Department of Transport, 2000). The mass properties of the prime mover and trailers were estimated using data provided by local manufacturers.

The optimisation routine was run for payload densities ranging from 50 kg/m³ to 800 kg/m³ to maximise payload subject to the constraints described above using the sequential quadratic programming (SQP) algorithm in MATLAB 2012 (Nocedal and Wright, 2006). To avoid integer constraints, the optimisation was run with 3 axles in each axle group and then repeated with the number of axles of the most under-loaded axle group reduced until no feasible solution could be found. The solution with the highest payload for each payload density was selected as the optimum.

3. Results

The results for total payload, SRT and RA are shown in Figure 4 to Figure 9 for truck and pig/tag trailer (TP) and truck and dog trailer (TDS) configurations.

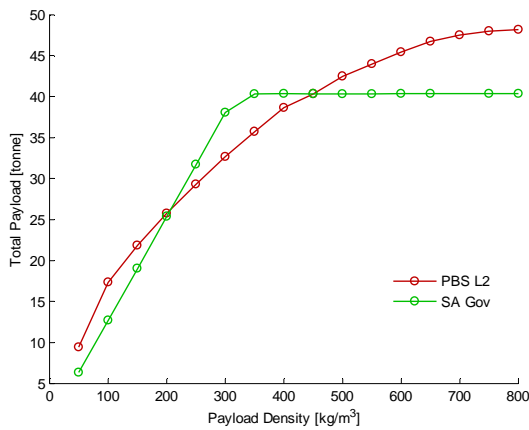


Figure 4 – TDS Payload

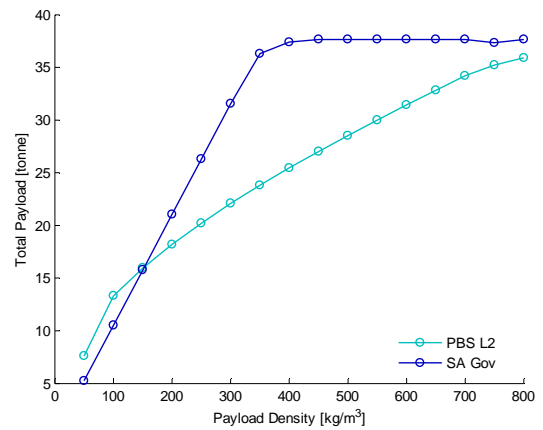


Figure 5 – TP Payload

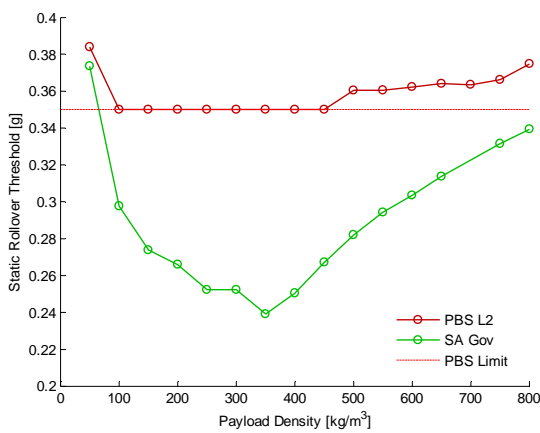


Figure 6 – TDS Static Rollover Threshold

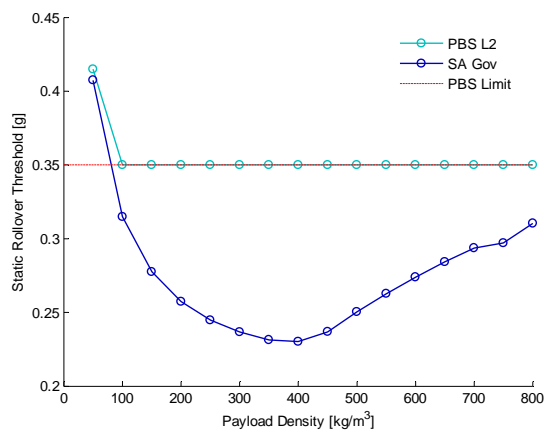


Figure 7 – TP Static Rollover Threshold

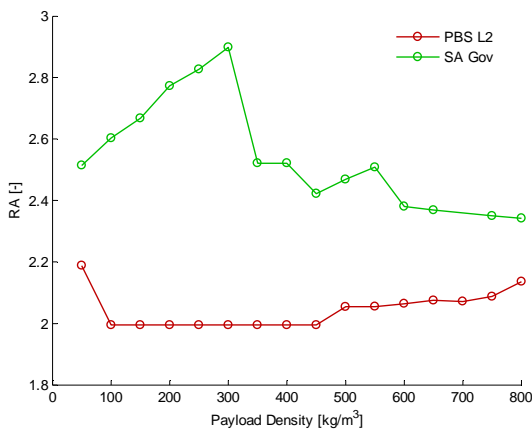


Figure 8 – TDS Rearward Amplification

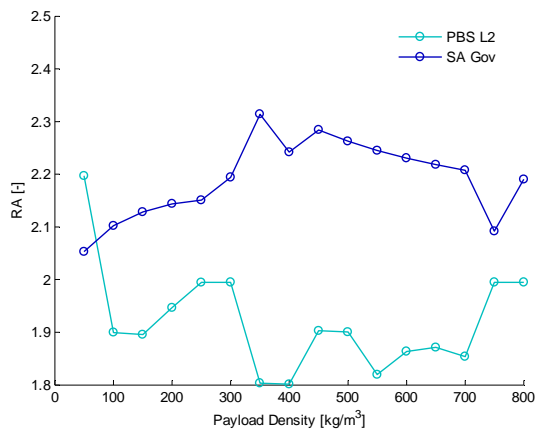


Figure 9 – TP Rearward Amplification

The total payloads of the PBS vehicles are less than those of the vehicles optimised for prescriptive South African legislation for payload densities of 200 - 450 kg/m³ for the TDS configuration and 150 - 800 kg/m³ for the TP configuration. This is due to the SRT constraint for both configurations and due to the RA constraint for the TDS configuration. The TP payload is much lower for the PBS vehicle because the SRT requirement forces the payload height to be lower but the configuration cannot take advantage of the additional overall length possible within the PBS framework.

The results for total payload, SRT and RA are shown in Figure 10 to Figure 15 for B-double (TBS) and A-double (TSDS) configurations.

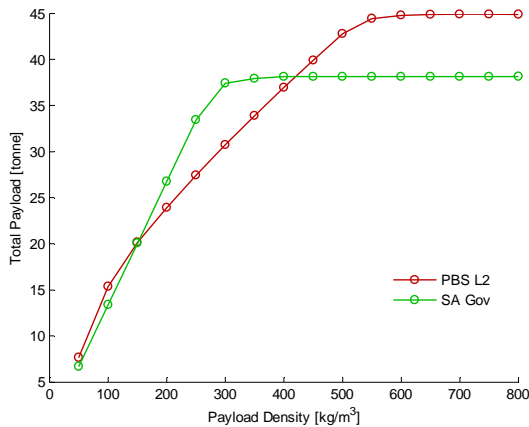


Figure 10 – TBS Payload

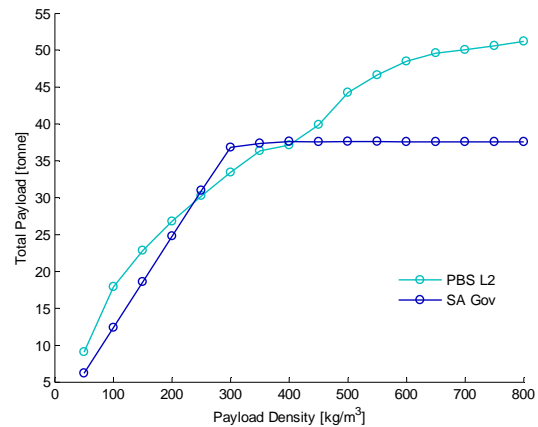


Figure 11 – TSDS Payload

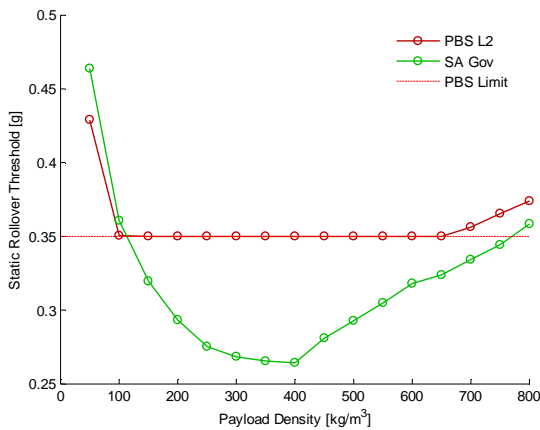


Figure 12 – TBS Static Rollover Threshold

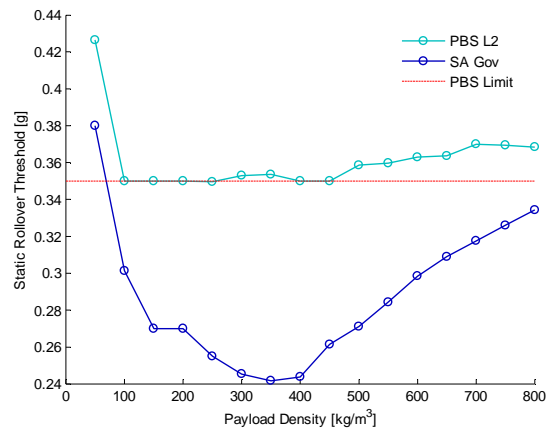


Figure 13 – TSDS Static Rollover Threshold

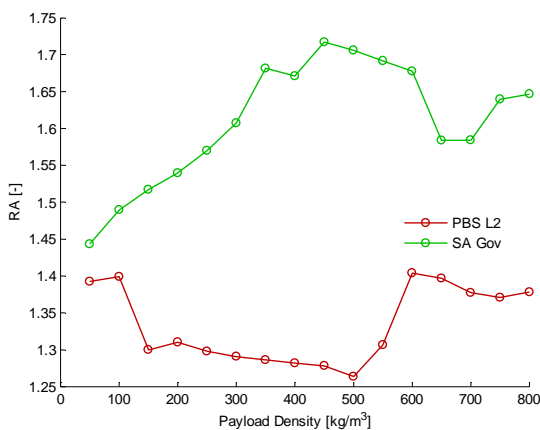


Figure 14 – TBS Rearward Amplification

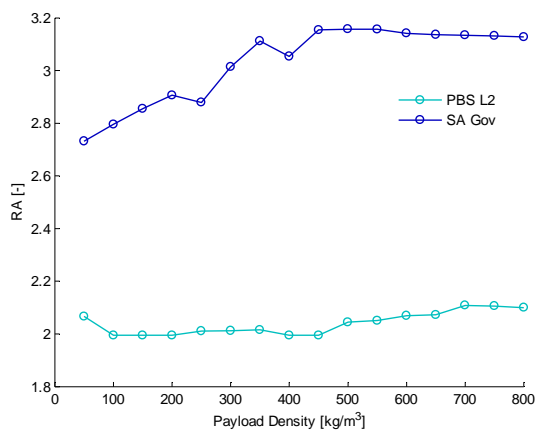


Figure 15 – TSDS Rearward Amplification

As with the TDS and TP configurations, the total PBS payloads of the TBS and TSDS configurations are lower than those of the prescriptive South African legislation equivalents due to the SRT constraint at payload densities of 150 – 370 kg/m³ and 150 – 400 kg/m³ respectively.

In all cases except for a payload density of 50 kg/m^3 for the TP configuration the RAs of the vehicles optimised for the prescriptive South African legislation are 10% poorer than the PBS designed vehicles. The SRTs of the vehicles optimised for the prescriptive South African legislation are below the PBS limit of 0.35 g for most payload densities with the worst occurring in the range of $300 - 400 \text{ kg/m}^3$.

With the exception of the TP configuration, all of the PBS optimised vehicles had LSSP equal to the PBS Level limit of 8.7 m . It is therefore recommended that further investigation is needed to evaluate the suitability of this limit for the South African road network.

4. Conclusions

1. The results indicate that heavy vehicles designed according to a PBS approach are safer than vehicles designed according to the prescriptive SA legislation: the prescriptive SA legislation vehicles have an RA that is 10% poorer than the PBS vehicles; and the prescriptive SRTs are below the PBS limit of 0.35 g for most payload densities with the worst occurring in the range of $300 - 400 \text{ kg/m}^3$.
2. Higher productivity payloads would only be realised using PBS-designed vehicles for payload densities greater than 400 kg/m^3 for the configurations considered within this study.
3. A methodology was demonstrated that allows for initial evaluation of vehicle configuration options and provides a good starting point for detailed design using full detailed simulation models. The method used equations with low enough computational cost to allow the use of optimisation routines to automate the vehicle design process. The method may be used to establish, for a given payload, whether a PBS design has the potential to offer a solution with improved productivity or safety (or both) without costly detailed design upfront.
4. The results from the study, used to demonstrate the use of the above methodology implemented in an automated design routine, will aid the South African road authorities in evaluating the potential benefits of introducing PBS legislation.

5. Acknowledgements

This research was partially supported by the National Research Fund (NRF) using the Technology and Human Resources for Industry Programme (THRIP) and Eskom using the Tertiary Education Support Program (TESP).

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